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Development Status of a 50k LOX/Hydrogen Upper Stage Demonstrator

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ABSTRACT

This paper discusses design and systems integration status of a 50,000 pound (222.4 kN) thrust Oxygen/Hydrogen Upper Stage Engine Demonstrator (USD) being created by Pratt & Whitney Liquid Space Propulsion under contract for the United States Air Force Research Laboratory (AFRL) to support the Integrated High Payoff Rocket Technology (IHPRPT) program. The objective of this program is to integrate advanced technology components into an expander cycle engine configuration and demonstrate a 1% increase in specific impulse, a 30% increase in engine thrust-to-weight, a 25% reduction in failures per 1000 uses, a 15% reduction in required support costs, and a 15% reduction in hardware costs relative to current state-of-the-art levels. Scheduled to be the first of the IHPRPT program engine demonstrators, test firing is planned in late 2001 to demonstrate a chamber pressure (Pc) capability of 1375 psia (9.48 Mpa). This integrated 50k LOX/LH2 engine demonstrator will be used to evaluate individual component technologies as well as the system level mechanical, structural and thermodynamic interactions.

This technology program pushes the performance and operability envelope of existing expander cycle engines and provides the technology foundation to allow the development of the next generation of advanced space propulsion systems for upper stage and reusable booster applications. Additionally, through design, manufacture, and integration of the demonstrator, new methods have been developed and adopted which will increase reliability and reduce component fabrication times.

INTRODUCTION

The Air Force, Army, Navy, and NASA have implemented a three-phase, 15-year rocket propulsion technology improvement effort to "double rocket propulsion technology by the year 2010." This initiative, designated the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) established performance, reliability, and cost improvement goals for each of the three phases. These goals are to be met by advancing component technology levels through design, development, and demonstration, followed by an integrated system level engine demonstrator to validate performance to the IHPRPT system level goals. Pratt & Whitney (P&W) Liquid Space Propulsion (LSP), under contract to the United States Air Force Research Laboratory (contract F04611-97-C-

0029), is conducting a system level integration of a 50k LOX/LH2 Upper Stage Demonstrator (USD) engine (Ref. AIAA 99-2475, *Design and Development of a 50k LOX/Hydrogen Upper Stage Demonstrator*). The USD is comprised of the Advanced Liquid Hydrogen (ALH) turbopump, which is currently undergoing tests (Ref. AIAA 2000-3679, *Testing of an Advanced Liquid Hydrogen Turbopump*), the Advanced Expander Combustor (AEC) (Ref. AIAA 2000-3776, *Fabrication And Test Of An Advanced Expander Combustor*), and P&W provided Advanced Liquid Oxygen (ALO) turbopump.

The ALH turbopump was designed and fabricated by P&W for the AFRL under contract F04611-94-C-0008 and is currently undergoing component testing at P&W. The ALH turbopump incorporates an advanced fluid film rotor support system and pump and turbine improvements to maximize pump discharge pressure at a minimum turbopump weight and production cost. The AEC thrust chamber was designed and is being fabricated by P&W for the AFRL under contract F04611-95-C-0123 for component testing with a P&W provided 50k injector in summer 2000. The AEC thrust chamber incorporates an advanced copper alloy in a tubular design to significantly improve the capability of the expander cycle engine. For the demonstrator contract effort, P&W is integrating the P&W provided ALO turbopump and 50k injector with the government furnished ALH turbopump and AEC thrust chamber, into a demonstrator assembly providing all required component physical and functional interfaces, ducting, valves, actuators, control system, instrumentation, and sensors.

The integration of these advanced technology components into an engine level system for test firing will demonstrate the IHPRPT LOX/LH2 boost/orbit transfer propulsion area Phase I goals. These system level goals include a 1% improvement in vacuum specific impulse, a 30% improvement in thrust-to-weight, a 15% reduction in hardware/support costs, and a 25% reduction in failure rate relative to the current state-of-the-art engine.

Pratt & Whitney, in cooperation with the AFRL, established an advanced upper stage expander engine model for the purpose of establishing the individual component requirements necessary to ensure the IHPRPT Phase 1 system level goals are achieved. This cycle model was used to establish the performance, cost, weight, and thermodynamic operating

requirements of the demonstrator engine. The component and engine level demonstration goals established for the 50k LOX/LH2 Demonstrator to support the IHPRPT goals are:

- Demonstrate an engine chamber pressure of 1375 psia (9.48 MPa) at an engine flowrate to provide 50,000 lb$_f$ (222.4 kN) of thrust
- Maintain the geometric envelope of the baseline (throat area, engine length and diameter, etc.)
- Traceable component weights to support an engine flight weight of 700 lb$_m$ (318 kg) and
- Demonstrate repeatable, safe, start, shutdown and steady-state operation

DISCUSSION

<u>System Integration Design</u>
With the design of the principal components, the ALH, AEC and ALO having been completed under separate contracts, the scope of the USD effort was limited to system integration. System integration of the USD piping was concluded with a successful Critical Design Review in September 1999. The Demonstrator is projected achieve the IHPRPT Phase I goal of 50,000 lb$_f$ (222.4 kN) thrust with margin. The projected vacuum specific impulse with a baseline area ratio nozzle will be 448.2 seconds. Extrapolating the design of the USD to estimated flight weights for the components indicates that the IHPRPT Phase I thrust-to-weight goal of 70.9 is achievable. Table 1 compares the USD and projected IHPRPT Phase I engine reliability improvements to the baseline engine. As the table indicates, the USD without the dual channel redundancy that would be incorporated into the IHPRPT engine design, is still projected to show a reliability improvement of 54% due primarily to the simplified valve designs and improved reliability of the fuel turbopump. Projecting the USD technologies into the IHPRPT Phase I engine, with the addition of dual channel control system redundancy, shows that the goal of a 25% percent reliability improvement is possible to achieve.

Figure 1 shows the current configuration of the USD. The design has changed very little since the Preliminary Design Review (PDR) in December 1998. The Agilis Group working in concert with P&W's Test and Design teams completed the design of the USD piping. Minor configuration changes have been made to the piping design to improve USD transient operation and assure the interface loads on the turbopumps, chamber and injector did not exceed requirements.

Both flow and structural analysis of the piping was performed. The flow analysis inlet conditions for each section were derived from the cycle analysis. The one-dimensional analysis indicates that at 100% RPL, improvements in pressure loss of 22% in the hydrogen system and 17% in the oxidizer system could be achieved compared to the initial math model expectations. The improvement in piping pressure drop assures that the turbine flow control valves have operative margin at the 100% RPL operating condition. The structural analysis includes the weight of the components and was performed at both 100% RPL and chill-down conditions to bracket the expected operating range. The analysis indicates all piping stresses are well within desired margins of

Component	IHPRPT Improvement Rational	Projected IHPRPT Phase I Engine	USD
		Component Improvement Relative to Baseline	
Valves	Simplified valve designs	44%	71%
Controls Components	Dual channel provides redundancy	24%	13%
Ignition System	Dual channel provides redundancy	26%	0%
Misc.		1%	3%
Gimbal Assy	Designed maintain margins		
Propellant Lines	Must meet EWR127-1		
Turbomachinery		6%	13%
Oxidizer Boost Pump			
Fuel Boost Pump	Factored from primary turbomachinery		
Oxidizer Pump Assembly	Simplified design offset by added turbine		
Fuel Pump Assembly	Simplified design (80% parts reduction)	5%	7%
Gearbox	Deleted		
Engine Total		77%	54%

Table 1 - USD, and IHPRPT Phase I Relibility Comparison
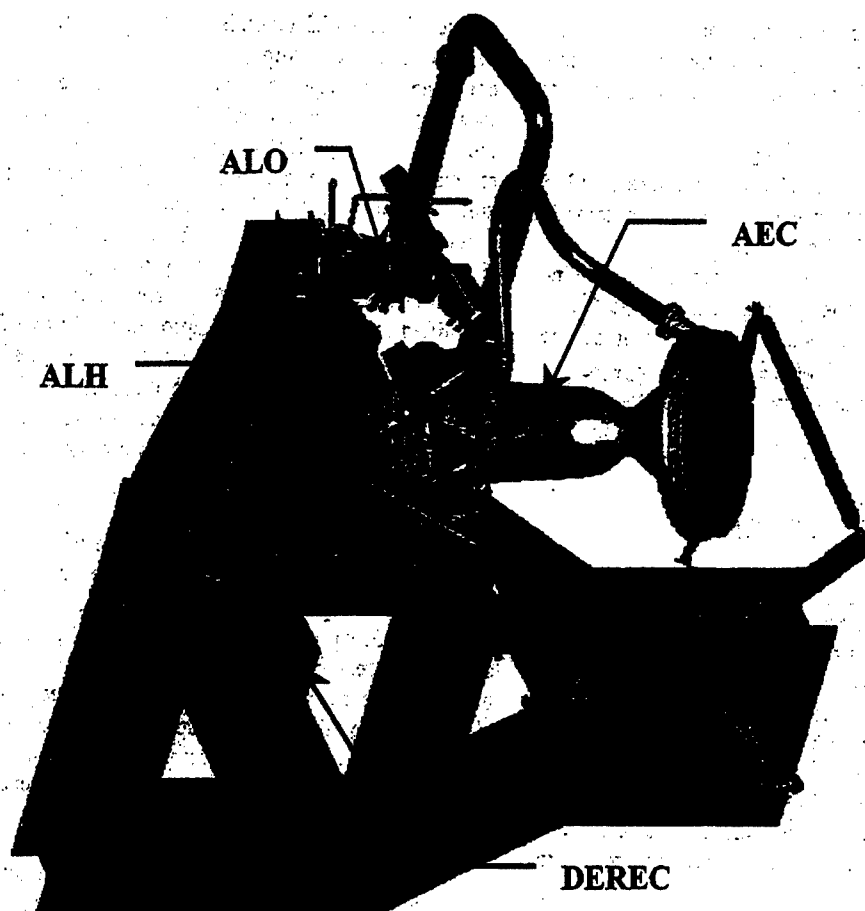
ALO

AEC

ALH

DEREC

Figure 1 - USD Configuration

safety for both static and vibratory conditions without imposing unacceptable interface loads on the components, which is adequate for the design intent of the USD. The thrust mount support ring was also examined and found structurally acceptable with end supports. The structural model will be retained to assist with the design of the discharge piping and other facility interfaces. The impact of the loads is expected to be low because of the current margins.

Over 150 individual sensors have been incorporated into the design of the USD to gather health monitoring and performance data on each of the components and the system in additional to the almost 20 parameters that will be monitored by the Digital Electronic Rocket Engine Control (DEREC). System data to be gathered include component fluid inlet and discharge conditions, inlet flow rates, turbomachinery rotational speeds and vibrations, valve positions and electromechanical Actuator (EMA) current draw.

USD Math Model

A USD system math model has been created with the P&W/NASA MSFC ROCket Engine Transient Simulation (ROCETS) system. ROCETS consists of a library of module building-block codes, a processor to configure the modules into a user defined system simulation and a processor to execute the simulation as defined by the user. The module codes are non-linear mathematical representations of the rocket engine components with sub-modules containing characteristic maps of specific components and properties of fluids, metals and combustion. Design, off-design and transient characterization are provided with the simulation through the use of characterized component maps. The transient ROCETS model represents the engine cycle and the component to component interactions with real properties (fluid and combustion) along with 2-dimensional flow analysis. Non-linear dynamic analysis of system interactions is achieved with volume dynamics, inertial flow, line friction losses, valve, actuator and controller

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characteristics. Heat transfer analysis is limited to 2-dimensional conduction and convection. The model does not perform any Computational Fluid Dynamics (CFD) analysis.

The USD ROCETS math model has both transient and steady state modeling capabilities within the limitations previously identified. This system level math model is used to establish start, power level ramps, shutdown and steady state valve schedule; support test planning and pre-run predictions; support component and plumbing design; define valve requirements; and verify control methodology. The USD math model is used to optimize transient and steady state operation with the following operability considerations:

- Avoid pump cavitation, stall, and overspeed caused by rapid flow acceleration, low inlet pressure and violation of suction performance;
- Minimize water hammer;
- Avoid injector flow reversals;
- Avoid nozzle throat over-temperature;
- Prevent thrust chamber erosion;
- Track requested thrust and mixture ratio; and
- Avoid excessive turbopump axial loads.

Several non-linear characteristics are incorporated in the USD math model. Combustion properties are obtained from the NASA ODE database and real fluid properties from the NIST database. The USD ROCETS model simulates:

- Volume dynamics;
- Pump inlet and discharge line inertia;
- Piping line losses and valve characteristics;
- Design and off-design turbine an polytropic pump characteristics;
- Multi-node chamber 2-dimensional heat transfer module;
- Injector areas;
- Controller with digital to analog interface actuator dynamics, sensor dynamics, and open or closed loop capability;
- Fuel system venturi; and
- Active injector purges.

Using the math model steady-state and transient operation were examined to develop control methodology and valve sequencing that would satisfy the operability considerations during start, power changes, steady-state and shut-down. Valve sequencing was optimized to minimize water hammer, avoid pump cavitation and similar turbopump related considerations, and reduce the potential of thrust chamber erosion during transients. Control methodology studies were performed to identify chamber pressure and mixture ratio controls, and set control parameters. Open and closed loop control simulations were run to validate the ability to control thrust and mixture ratio to the requested set-points. ALH and ALO turbopump performance maps will be benchmarked against component performance test results to assure sufficient cooling of the thrust chamber. The effects of injector purge activation on propellant fill and flushing were examined. The math model enables customization of system control parameters to safely optimize USD operation.

USD Math Model Updates:
The USD system math model will be updated to reflect component characteristics based on final design and component test results. The USD system math model has been updated to reflect the final design configuration piping line losses. The ALO performance maps were available December 1999. Limited steady state analysis was completed with these component updates, discussed below. Valve characteristics were available late in 1999. Verification of the valve flow data will be completed prior to updating the math model. AEC component characteristics will be available in mid 2000, following hot fire testing of the AEC. ALH component characteristics will be available upon completion of the ALH test series.

Transient Analysis:
The transient studies will be repeated upon having the off-design characteristics from component testing of the ALH, ALO and AEC incorporated into the model. The coupling of these components and the system dynamic characteristics requires that final transient studies be deferred until all benchmarked component characteristics are available. Analysis of turbopump axial loads will be completed after ALH and ALO component characteristics have been validate by test and the results incorporated into turbopump axial load modules.

Steady State Analysis:
The USD math model was used to analyze the preliminary steady-state performance at power levels ranging from the start level, 60% RPL - Pc of 825 psia (5.69 Mpa) at an O/F of 6.0, to the 100% power level, Pc of 1375 psia (9.49 Mpa) at an O/F of 6.0. The updated ALO performance maps result in no significant change in the steady-state operating points analyzed. The piping line losses resulted in a 3.5% increase in fuel control valve margin at the 100% RPL point. Complete steady-state analysis, including the off-
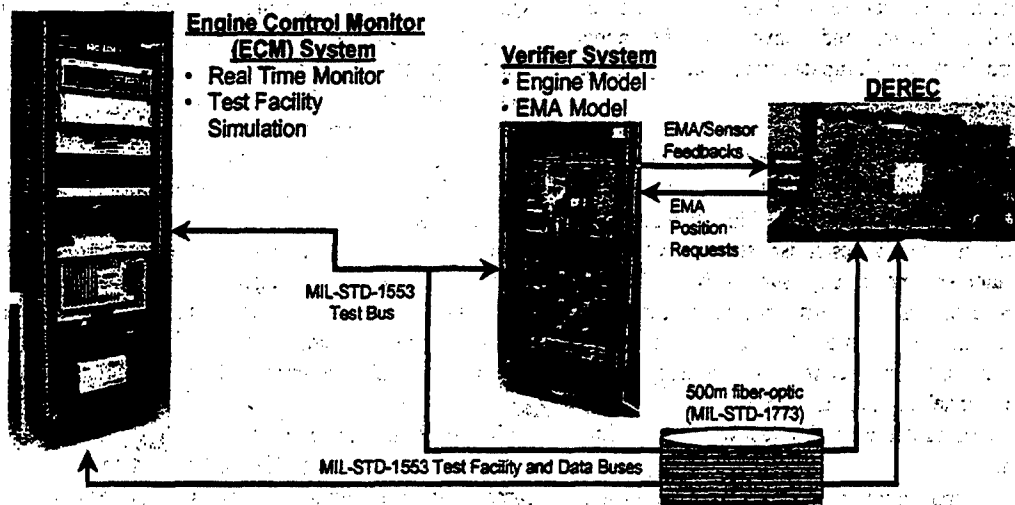
Figure 2 - The DEREC Software Verification System

design points and turbopump axial loads will be deferred until benchmarked component characteristics are available.

Digital Electronic Rocket Engine Control (DEREC)

The 50k engine demonstrator will be configured with an "on-engine" electronic control system. The engine control system will be comprised of a Digital Electronic Rocket Engine Control (DEREC) system and electromechanical actuators (EMAs) to control the engine valves. EMAs eliminate the need for conventional hydraulic actuators and pumps, supply lines, and associated ground support equipment, directly supporting the IHPRPT cost, weight, and reliability goals.

The DEREC receives thrust and mixture ratio commands from the test stand computer and modulates the rig EMAs to achieve the desired test article response. While both the DEREC and EMAs have two fully redundant electrical channels, only one channel will be active for the demonstrator test program. Use of a DEREC with EMAs with redundant channels is expected to provide an IHPRPT Phase I engine with a 45% reduction in failure rate, through improved engine control, electrical signal redundancy, and elimination of the pneumatic actuation system. The demonstrator DEREC will communicate with the test facility through a MIL-STD-1553 data interface through an Engine Control Monitor (ECM). An abort command can be sent directly from the test stand computer to terminate the test should the facility health monitoring system detect an out-of-limit condition.

The embedded software will control the demonstrator through all phases of operation – prestart conditioning, start, steady-state, and shutdown, and will include limited self-health monitoring, fault detection, and fault accommodation functions. While both chamber pressure and mixture ratio control functions will be open loop with command set-point being issued by the Test Conductor, the DEREC software will include a limited authority closed loop trim function that can be activated during testing.

DEREC software has been written and bench checkout of the software is in progress using a Software Verification System which incorporates a Verifier to simulate the engine and EMAs (Figure 2). The Verifier has a real time model that simulates engine operations and EMA feedback for all stages of engine operation. DEREC software test cases have been completed to verify all engine operating conditions as well as sensor performance, activator response, and all control models. Software test cases are presently being run to verify DEREC self-health monitoring and test stand communications.

Once characterization of USD components is complete, software schedules and constants will be reviewed. If necessary, the software will be updated and all changes will be re-tested to ensure proper operation.

The Verifier System will also be used for test simulation during demonstrator testing. Prior to running the test command sequence on the USD rig,

the test will be simulated using the Verifier to validate proper and safe operation.

Integration Test

Software and hardware integration testing was performed at the bench level to verify control system compatibility. The latest USD rig test DEREC software was utilized. Engine cycle operation was simulated in a similar fashion to that planned for typical test operations. The limited authority closed loop trim function in the DEREC software was also evaluated during this testing.

Critical software testing was completed using the Software Verification System described in section 4 prior to the integration test. This minimized hardware risk by insuring that all vital control and fault accommodation functions were tested and operating properly.

Hardware Setup
Figures 3 and 4 provide a photo of the actual test setup and a functional block diagram of the bench

configuration. This setup is nearly identical to the Software Verification System with exception of actual EMAs were used instead of the simulated electrical loads provided by the Verifier.

Test Operation
During normal Software Verification System operation the Verifier sets chamber pressure, using the real time DEREC commanded EMA /As in place instead of the ommand function of the ECM, ed instead of the real-time figuring the system with the s of operation were run using sition requests were recorded ne data recording system. The s for real-time data playback to -STD-1553 test bus. The result ment consistent with DEREC rig test mode.

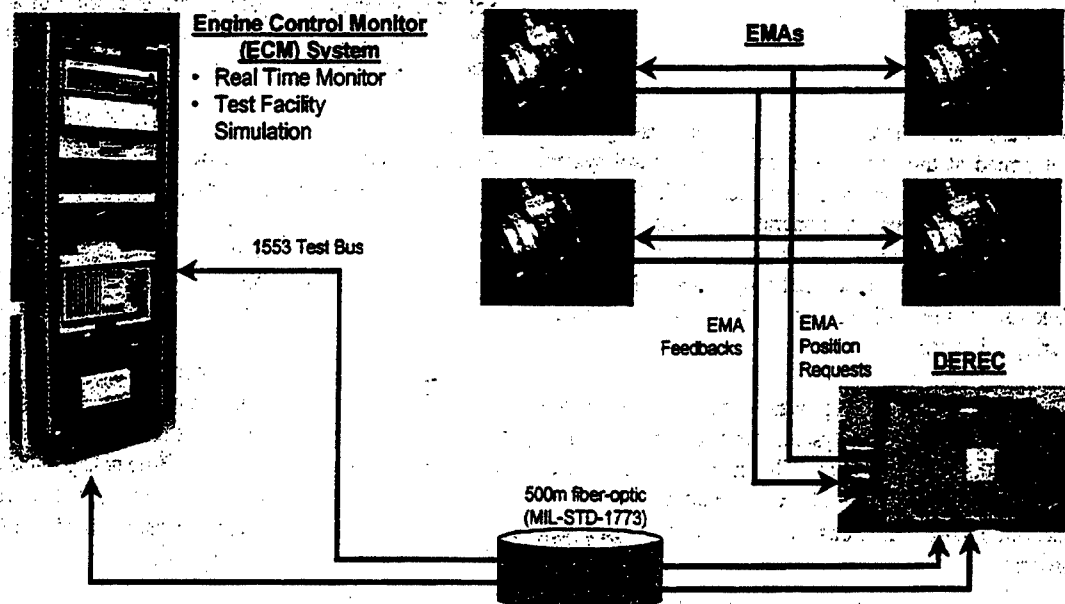
Figure 4. Integration Test Hardware Setup

Figure 3 - Integration Test System

Hardware Status

Assembly of the USD is being paced by component tests of the ALH and AEC. Component testing of the AEC is scheduled for completion 3rd quarter of 2000. Component testing of the ALH is expected to be completed 1st quarter of 2001. The ALO has completed component tests, and the turbopump is stored at P&W awaiting USD test. Manufacture and water flow calibration of the USD control valves has been completed by Flodyne Controls. The EMAs are all on hand and their operational status has been verified. Fabrication of the control system wiring harnesses is over 95% complete. All materials are on-hand needed to fabricate the Demonstrator piping. Once testing of the components is completed they will be used to field fit the piping during the 1st quarter 2001. Assembly of the USD is expected to require less than a week once the piping fabrication has been completed.

Testing of the USD will be conducted on P&W's High Pressure Cryogenic Test Facility and is planned to start in the 3rd quarter 2001 once the DEREC software has completed validation test.

Summary

The operating conditions and design features of the USD components were selected to demonstrate IHPRPT Phase I goals. The IHPRPT goals are broad based and were selected to focus efforts to improve all aspects of rocket propulsion systems. Successful completion of the program will provide the confidence and design validation to transition the demonstrated advanced technology components into existing and future propulsion systems.

The primary enabling technologies (fluid film bearings, high-heat transfer chamber, and digital controls) will demonstrate significant benefits for rocket engine components regardless of cycle or propellant combination. Future vehicles such as the Space Operations Vehicle and Space Maneuvering Vehicle will need very high performing propulsion systems. The USD provides a demonstration of advances that can benefit these propulsion systems.

While the USD was designed to provide an IHPRPT Phase I upper stage demonstrator, it was sized to meet future launch system demands. The thrust level for the upper stage demonstrator is based on future launch vehicle demands. This is already evident on Atlas and Delta heavy lift configurations that use two RL10 engines. An engine based on the USD meeting the IHPRPT Phase I goals for thrust-to-weight and

manufacturing/support costs will be able to replace these two engines in the same envelope of just one RL10, increasing vehicle reliability and reducing overall vehicle cost.

With cost being one of the primary focus areas of the IHPRPT goal, the USD has also developed procedures and manufacturing techniques which will reduce the overall cost to launch vehicles in both hardware and support requirements. This supports the EELV program goals of reducing launch costs by 25 to 50%. Engines utilizing the technologies demonstrated by the USD will directly benefit any future upgrades to EELV launch vehicles. The higher thrust level and maintaining the same operational envelope of the RL10 also supports the demands of the heavy lift EELV.

The USD will demonstrate the operation of a high conductivity chamber, fully supported fluid film bearing turbopump and digital controls in an engine configuration. This technology demonstration, scheduled for testing in late 2001, will push liquid rocket engine performance to new levels. This technology base can lead to a highly reliable, reduced cost engine capable of replacing existing RL10 upper stage engines. The USD will lead to robust engines for future expendable applications.

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